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August 11, 1970

MEMORANDUM

TO: P. L. ROGGENKAMP

FROM: T. C. GORRELL TCG

^{135}I YIELD FROM ^{245}Cm FISSION

INTRODUCTION

Each of the ^{242}Pu outer housings in the Cf I lattice now contains about 0.5 g of ^{245}Cm. Because the fission cross section of ^{245}Cm and the thermal flux in Cf I are both relatively high, the ^{135}I concentration in these targets is also high, and decays to ^{135}Xe worth several percent in k_{eff} during shutdown intervals. The reactivity worth of the target xenon must be known to determine the "real" margin of control, i.e., the margin of control of a new fuel lattice if no target xenon were present. Tests to measure the worth of the xenon are conducted, immediately following reactor startup, every 5 or 10 fuel cycles. In the tests, the control rod position vs. time is measured as power is held constant at $\sim$100 MW for about 2 hours to burn up the xenon. In one such test, for the K-46 fuel cycle, the results were used as part of a

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group of calculations to infer a yield of ^{135}I from ^{245}Cm fission. The method used was to determine the ^{135}I yield value that would produce a ^{135}Xe concentration, which with the HAMMER-HERESY-HETERO codes was calculated to give the measured reactivity worth.

SUMMARY

A value of .041 was inferred as the ^{135}I yield for ^{245}Cm fission from the test made as part of the K-46 cycle startup. Although the yield value of .041 is low compared with the corresponding values for ^{235}U, ^{239}Pu and ^{241}Pu, there is experimental evidence that for higher fissionable isotopes, a significant part of the ^{135}Xe appears as a direct yield, and does not contribute to the shutdown transient. Measurements of the ^{135}I and ^{135}Xe yields are now being made by the Separations Chemistry Division with ^{249}Cf and ^{245}Cm.

DISCUSSION

Xenon Test Data

Rod Worth Relationship

The control rod worth curve for rod positions of interest in this analysis was calculated with the CRUD code, which solves the equation

$$\nabla^2 \phi(Z) + \left[B_{fuel}^2 (Z) - B_{rods}^2 (Z) \right] \phi(Z) = 0 ,$$

utilizing 728 axial regions. Input parameters include B^2 of the fuel lattice and worths for all combinations of control rods. The code finds the rod complement required to satisfy the above equation. In this case, the initial value for B^2 fuel was chosen such that the corresponding full rod complement was 5000 vu, with the partial rods at 1000 vu. The partial rods were then set at 733 vu, and the B_{fuel}^2 value reduced in 5 μB increments, up to a total B_{fuel}^2 change of 200 μB. The full rod positions calculated by CRUD were plotted against ΔB_{fuel}^2. The full rods were in three trim groups, having trim values of 0, 333 and 666 vu, respectively. A similar curve calculated by another method(1) is also shown. The agreement is very good.

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Xenon Burnup Test

The test was conducted as part of the nuclear startup of the K-46 fuel cycle. The K-45 cycle had been a clean, no-scram cycle that ran to an exposure of 5280 MWD and operated at a power of about 1300 MW. The shutdown interval between K-45 and K-46 was 13.5 hours, a time at which the xenon concentration in the target assemblies was within 5% of its maximum value. The reactor was made critical, power was raised promptly to 100 MW and held constant for two hours. Full control rods were inserted in Gangs I and II to compensate for the reactivity added from the burnup of xenon in the target assemblies. Approximately 1600 veeder units of rod was inserted in all. The reactivity equivalent of the rod addition is shown in Figure 2. The points were derived from rod position data obtained at one minute intervals, and from the CRUD curve in Figure 1.

Reactor power was being raised for the first 8 minutes that rod data were taken, as shown in Figure 2. Subsequent reactivity changes are due to xenon burnup. The reactivity added in control rods is equal to the difference between 208 μB and 23 μB, or 185 μB. The slight irregularity in the curve at 25 minutes elapsed time is unexplained. Ideally, the curve would be a smooth exponential.

The measured change in control rod reactivity of 185 μB was caused primarily by the burnup of xenon in the target assemblies. A smaller, but significant effect, occurred near the end of the test as xenon built into the new fuel assemblies from ^{235}U fission.

Calculated Reactivity Changes

It it is assumed that the concentrations and fission cross section of ^{245}Cm in the target assemblies are known, it is possible to obtain an ^{135}I yield value for ^{245}Cm fission from the test data by making a series of lattice reactivity calculations.

The following parameters are required to calculate the xenon reactivity effects during the test.

1. Neutron flux in the target assemblies prior to K-45 shutdown.
2. ^{245}Cm concentration in the target assemblies.
3. Fission cross section of ^{245}Cm.
4. Length of zero flux interval.
5. Neutron flux in targets and fuel during test.

[redacted]

6. ^{235}U concentration in the K-46 fuel.

7. Fission cross section of ^{235}U.

8. ^{135}I yield for ^{235}U fission.

9. ^{135}I yield for ^{245}Cm fission.

The last parameter on the list can be obtained by varying its value until the calculated reactivity change is equal to the measured change. Initially, it will be assumed all ^{135}I originates from ^{245}Cm fission only. A brief description of how the other parameters were obtained is given below.

The target flux at the end of the K-45 cycle was calculated from the beginning fuel content, the assembly exposure (MWD), the fission power, and the calculated target/fuel flux ratio. The flux value used in the calculations was about 5% less than the cycle end flux, to obtain an iodine concentration representative of the last several hours of the cycle.

The ^{245}Cm concentration was obtained from APE calculations, which evaluate the buildin of curium isotopes in target assemblies originally containing only ^{242}Pu. The target exposures were obtained from measured fuel exposures and calculated target/fuel flux ratios.

The reactor-average neutron flux in the fuel and targets during the test was fixed at the value corresponding to a reactor power of 100 MW. The radial distribution, from assembly to assembly, was obtained from HERESY calculations.

The fuel assemblies were divided into 5 radial groups, corresponding to increasing radial distance from the reactor center and decreasing ^{242}Pu content. The Am-Cm Q-foils made up a sixth group.

Parameters for each group are given below.

TABLE I

Target Assembly Concentrations and Fluxes

Pu Group	Number of Assemblies	^{245}Cm Concentration, g/assembly	Target Assembly Neutron Flux, n/cm^2-sec End K-45 Cycle	Test
1	12	.47	5.8×10^{15}	2.9×10^{14}
2	18	.47	5.2	2.6
3	18	.49	5.2	2.5
4	18	.44	4.5	2.0
5	24	.08	4.2	1.6
Q-foils	6	.94	5.8	2.9

A list of other nuclear parameters is given below.

Fission cross section of ^{245}Cm (90°C)	1604 b
Fission cross section of ^{235}U (20°C)	458 b
Length of zero flux interval	13.5 hours
Yield of ^{135}I (^{135}Xe) in ^{235}U fission	.062 (.002)

Note that the ^{245}Cm fission cross section was evaluated at 90°C moderator, and the ^{235}U value at 20°C. This is necessary because the ^{245}Cm fissions occurred at the end of the K-45 cycle at full power, and the ^{235}U fissions occurred at a very low power during the K-46 startup.

The standard equations for iodine and xenon concentrations were used, and are given here. The results are in terms of number densities, for ease of preparing HAMMER input.

Concentrations in Targets at Shutdown

$$I_{SD} = (\text{yield})(\phi_{SD})(\sigma_f N)_{245}/\lambda_I$$

$$Xe_{SD} = (\text{yield})(\phi_{SD})(\sigma_f N)_{245}/(\lambda_{Xe} + \sigma_a^{Xe}\phi_{SD})$$

where:

yield = result to be obtained, ^{135}I yield

subscript "SD" implies at shutdown

$\lambda_I = 2.882 \times 10^{-5}$/sec

$\lambda_{Xe} = 2.093 \times 10^{-5}$/sec

$\sigma_a^{Xe} = 2.93 \times 10^6$ barns

Concentrations in Targets at Start of Test

$$I_{ST} = (I_{SD})\, e^{-\lambda_I t}$$

$$Xe_{ST} = \frac{(I_{SD})(\lambda_I)}{\lambda_{Xe} - \lambda_I}\left[e^{-\lambda_I t} - e^{-\lambda_{Xe} t}\right] + (Xe_{SD})\, e^{-\lambda_{Xe} t}$$

where:

subscript "ST" implies start test

$t = 13.5$ hours

Less than 0.5% of Xe_{ST} originates from the second term, which means the Xe concentration at reactor shutdown is not an important factor in the zero-flux xenon transient.

[redacted]

Concentrations During Test

1) Decay and burnup of target xenon

$$\text{Xe 1)} = (Xe_{ST})\, e^{-(\lambda_{Xe} + \sigma_a^{Xe}\, \phi_T)t}$$

2) Xenon originally held up as iodine-135

$$\text{Xe 2)} = \frac{(I_{ST})(\lambda_I)}{(\lambda_{Xe} - \lambda_I + \sigma_a^{Xe} \phi_T)} \left[e^{-\lambda_I t} - e^{-(\lambda_{Xe} + \sigma_a^{Xe} \phi)t} \right]$$

3) Xenon building in from new ^{245}Cm fissions

$$\text{Xe 3)} = \left[\frac{(\text{yield})(\phi_T)(\sigma_f N)_{245}}{\lambda_{Xe} + \sigma_a^{Xe} \phi_T} \right] \times \left[1 - e^{-(\lambda_{Xe} + \sigma_a^{Xe} \phi_T)t} \right]$$

$$+ \left[\frac{(\text{yield})(\phi_T)(\sigma_f N)_{245}}{\lambda_{Xe} - \lambda_I + \sigma_a^{Xe} \phi_T} \right] \times \left[e^{-(\lambda_{Xe} + \sigma_a^{Xe} \phi_T)t} - e^{-\lambda_I t} \right]$$

where:

t = elapsed time after start of test

ϕ_T = target neutron flux during test

An expression similar to 3) above is also used to calculate new xenon appearing in the fuel from ^{235}U fissions, with appropriate values for the yield, σ_f and N for ^{235}U being used.

[redacted]

A short FORTRAN program was written for the IBM 360/65 to facilitate calculation of the ^{135}Xe number densities.

A few simple, reactor-average calculations were made to estimate a yield value for ^{135}I from ^{245}Cm fission that should be used in a detailed calculation. A yield value of .040 was chosen from these results, as a reasonable first guess.

In the detailed calculation, the xenon concentrations in fuel and target were calculated at 15 minute intervals of the test for a yield value of .040. HAMMER-HERESY calculations were made for each case, and were used to prepare the input for the 3D HETERO code, which can accommodate the different target and fuel lengths. HETERO control rod parameters were fixed at the value required for criticality for the no xenon case. The HETERO k_{eff} values are given in Figure 3.

The calculated change in reactivity that occurred during the test period was .0450 k(.993-.948), for the yield value of .040.

The M^2 of the lattice with no xenon present was 273 cm^2. If ΔB^2 is calculated from the expression $\frac{\Delta k}{M^2}$, a value of 165 μB is obtained for ΔB^2. A yield value of .045 for ^{135}I in the calculations (vice .040) would have resulted in a calculated ΔB^2 of 185 μB (.051 Δk_{eff}), the measured difference. Detailed calculations were not repeated for a yield value of .045.

The worth of new xenon in the fuel at the end of the test was .005 Δk_{eff}, and the remaining target xenon was worth .002 Δk_{eff}. The worth of target xenon at the beginning of the test is equal to the sum of the measured change (target xenon burned up or decayed), the target xenon remaining, and the fuel xenon, or .051 + .005 + .002 = .058 Δk_{eff}.

A plot of fractional reactivity change during the test is given in Figure 4, for the calculated and measured values. The results show that flux values used in the xenon equations for 100 MW were very close to the actual values, because the equilibrium reactivity condition in both curves was reached after 70 minutes of xenon burnup. The agreement is sufficiently good to infer the yield value of .045 discussed in the previous paragraph.

[redacted]

Figure 5 shows the relative worth of target and fuel xenon calculated during the test. After 90 minutes operation at 100 MW, the target xenon is 3% of its value at the start of the test, and the fuel xenon is worth 9% of the initial target xenon. The time t = 0 in Figures 3, 4 and 5 corresponds to t = 8 minutes in Figure 2.

One deficiency in the calculations is the fact that the HETERO k_{eff} values were not 1.0 in each case. Instead, the control rod Σ_a was fixed at that value which gave a k_{eff} of 1.0 for the no xenon case. Ideally, the HETERO control rod Σ_a value would be changed, analogous with the control rod insertion of the actual test.

A series of HERESY calculations was made to show that no large errors occur in evaluating ΔB^2 from $\dfrac{\Delta k_{eff}}{M^2}$ or from considering k_{eff} differences in a system that is 5 or 6% subcritical. The absolute values for ΔB^2 cannot be compared directly with measured results because HERESY is only two dimensional, but it is reasonable to assume that any conclusions drawn here would also be applicable for HETERO Δk results. The HERESY results are given below.

TABLE II

HERESY Calculation Results

Case	Description	Control Rod f Value	B_{Ax}^2, μB	ΔB^2, μB	k_{eff}	Δk_{eff}	M^2	$\left(\dfrac{\Delta k_{eff}}{M^2}\right)$
1	No xenon	.99514	150	-	1.0	-	284	-
2	No xenon	.99514	373	223	.9370	.0630	284	222
3	No xenon	.99209	373	-	1.0	-	302	-
4	Full Target xenon	.99209	373	-	.9350	.0650	292	223
5	Full Target xenon	.99209	151	222	1.0	-	292	-

Comparing cases 1 and 2, the ΔB^2 of 222 μB calculated by $\Delta k_{eff}/M^2$ (.0630/284) is in good agreement with the ΔB_{Ax}^2 of 223 μB. Similarly, the ΔB_{Ax}^2 of 222 μB (cases 5 and 3)

[redacted]

calculated as the worth of target xenon at the start of the test is in good agreement with $\Delta k_{eff}/M^2$ (.0650/292). Any computational technique which would relate control rod parameters and buckling would involve relationships just like those described. It is concluded that a satisfactory alternative is to fix the control rod parameter, obtain Δk_{eff} between the critical and subcritical systems, and evaluate ΔB^2 from $\Delta k_{eff}/M^2$.

Corrections

Target Fissions from Other Isotopes

APE calculations show that for the conditions existing at the time of the test, ^{245}Cm fissions account for 92% of all target fissions. The other significant contribution is from ^{244}Cm. If it is assumed both isotopes have the same ^{135}I yield, the yield from ^{245}Cm fissions inferred from the test should be .045 x .92 or .041.

Changes in ^{149}Sm Concentration

A CINDER[2] calculation was made to evaluate the changes in ^{149}Sm concentration that occurred during the test. The cross sections for ^{135}Xe and ^{149}Sm in the CINDER library differ from those in the HAMMER library, but are sufficiently close for this comparison. The CINDER calculations show that the Sm concentration increased only 4% during the test period, a small change compared to the ^{135}Xe change. It is interesting to note that (at the K-45 shutdown) CINDER calculates a ^{149}Sm worth equal to that for ^{135}Xe. At the startup of the K-46 cycle, the xenon worth has increased by about a factor of 100, and the Sm worth by a factor of 6. Seven different fission product chains contribute to ^{149}Sm in CINDER, with six involving one or more neutron captures.

Although the reactivity worth of ^{149}Sm is significant compared to the ^{135}Xe worth, the change in ^{149}Sm during the test can be disregarded. In fact, the CINDER results for total fission product Σ_a showed that only the ^{135}Xe concentration changed significantly during the test.

Possible Sources of Error

Three parameters that affect the calculated yield strongly are those in the numerator of the iodine equation, namely, the target flux at shutdown, the fission cross section of ^{245}Cm and the concentration of ^{245}Cm. The uncertainty in the flux should not exceed 5%. The uncertainty in the product $(\sigma_f N)_{245}$ is somewhat larger, perhaps as high as 10%.

[redacted]

The rod worth curve is a possible source of error. However, the curve generated by the CRUD code and the curve appearing in reference 1 agree very well. Both curves would be in error by the same amount if the reactivity worths of the 5, 6 and 7 rods were incorrect. No rod worth values were measured for the Cf I lattice. Values used are those measured for the 1965 High Flux Charge, with appropriate factors applied for differences in radial statistical weights and fuel loadings.

Conclusions

A value of .041 for ^{135}I yield from ^{245}Cm fissions is inferred from the test results. No effects besides ^{135}Xe buildin or burnup made significant reactivity contributions during the test. The value of .041 is substantially lower than would be expected, based on the ^{135}I yields of the isotopes ^{235}U, ^{239}Pu and ^{241}Pu. Some of the yields are shown below. A value of about .06 might be expected for ^{245}Cm, based on these data.

Fission Product	Yield			
	^{235}U	^{239}Pu	^{241}Pu	^{245}Cm
Te 130	.020	.025	.022	-
I 131	.025	.032	.029	.032
Te 132	.044	.053	.048	.044
I 133	.066	.069	.060	.060
Xe 134	.081	.075	.064	-
I 135	.062	.069	.063	-
Xe 135	.0024	.0027	.0024	-
Xe 136	.065	.066	.066	-
Cs 137	.062	.065	.064	.079
Ba 138	.057	.063	.063	-
La 139	.066	.060	.062	-
Ba 140	.064	.055	.060	.057
Reference	2	2	2	3

[redacted]

However, there is experimental evidence that for the isotope ^{249}Cf, about 40% of the ^{135}Xe originates as a direct yield, rather than from ^{135}I decay. These results are preliminary, and are part of a program being conducted by the Separations Chemistry Division. Calculations using charge distribution systematics imply that about 30% of the ^{135}Xe from ^{245}Cm fission originates as a direct yield. The corresponding ^{135}I yield would be 4.0 to 4.5%. Experimental data for these yields will be obtained in the near future.

The calculated reactivity effects are independent of the direct ^{135}Xe yield. If the ^{135}I value measured by ACD is indeed 4.0 to 4.5%, that results would be in excellent agreement with the reactivity test and calculations.

TCG:vpb

REFERENCES

(1) DPSP-69-1349, "Californium I Physics Information," F. D. Benton, August 5, 1969, Secret.

(2) DPST-68-262, Rev. 1, "CINDER - Description and Application," J. B. Pye and W. R. Cornman, February 12, 1970.

(3) Physical Review - Vol. 161, No. 4, 20 September 1967, "Distribution of Mass and Charge in the Fission of ^{245}Cm." H. R. Von Gunten, et al.

[redacted]

Fig 1 Rod Worth Curve, Cf I Lattice

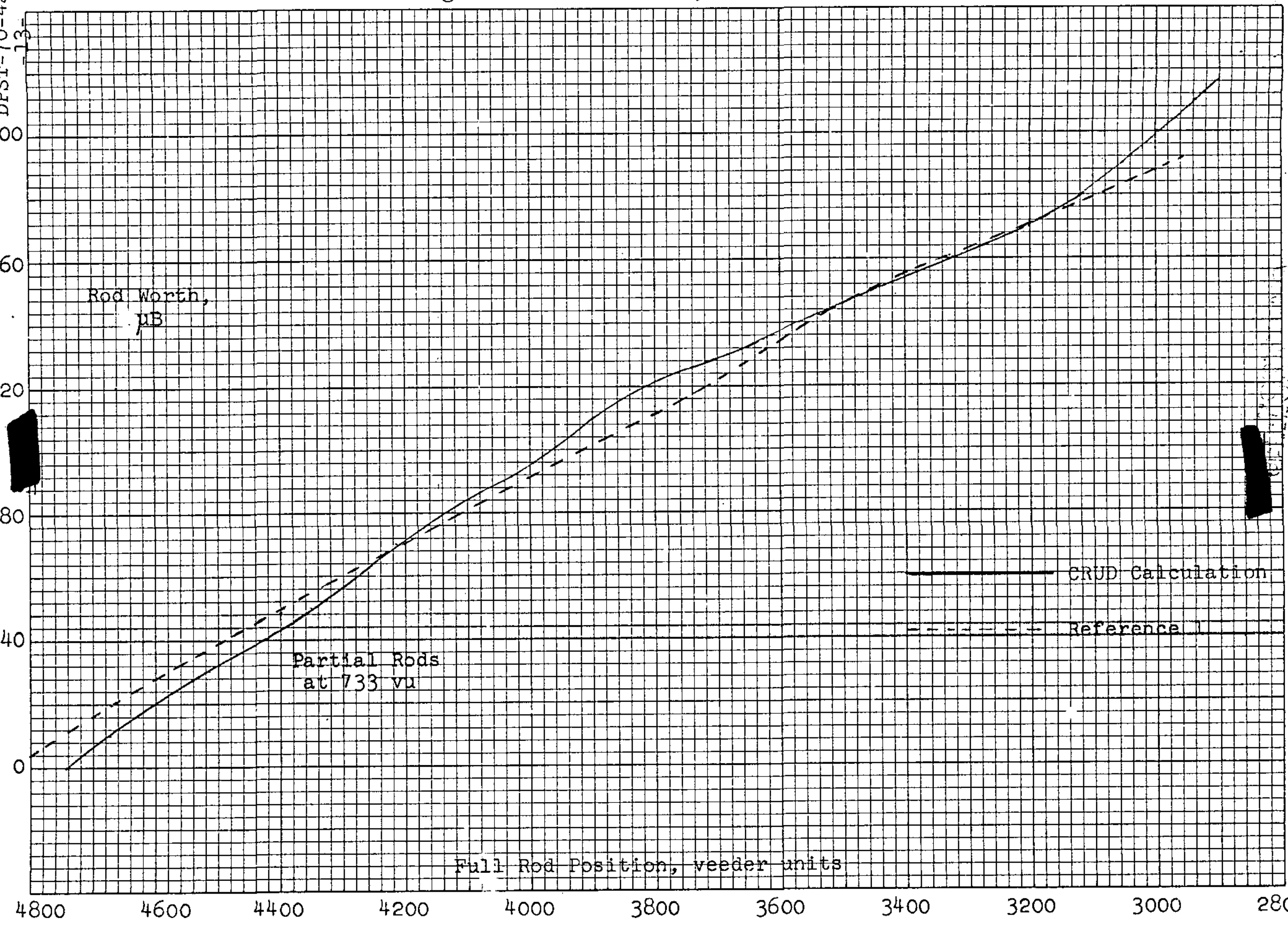

Fig. 2 Reactivity Change from Xenon Burnup

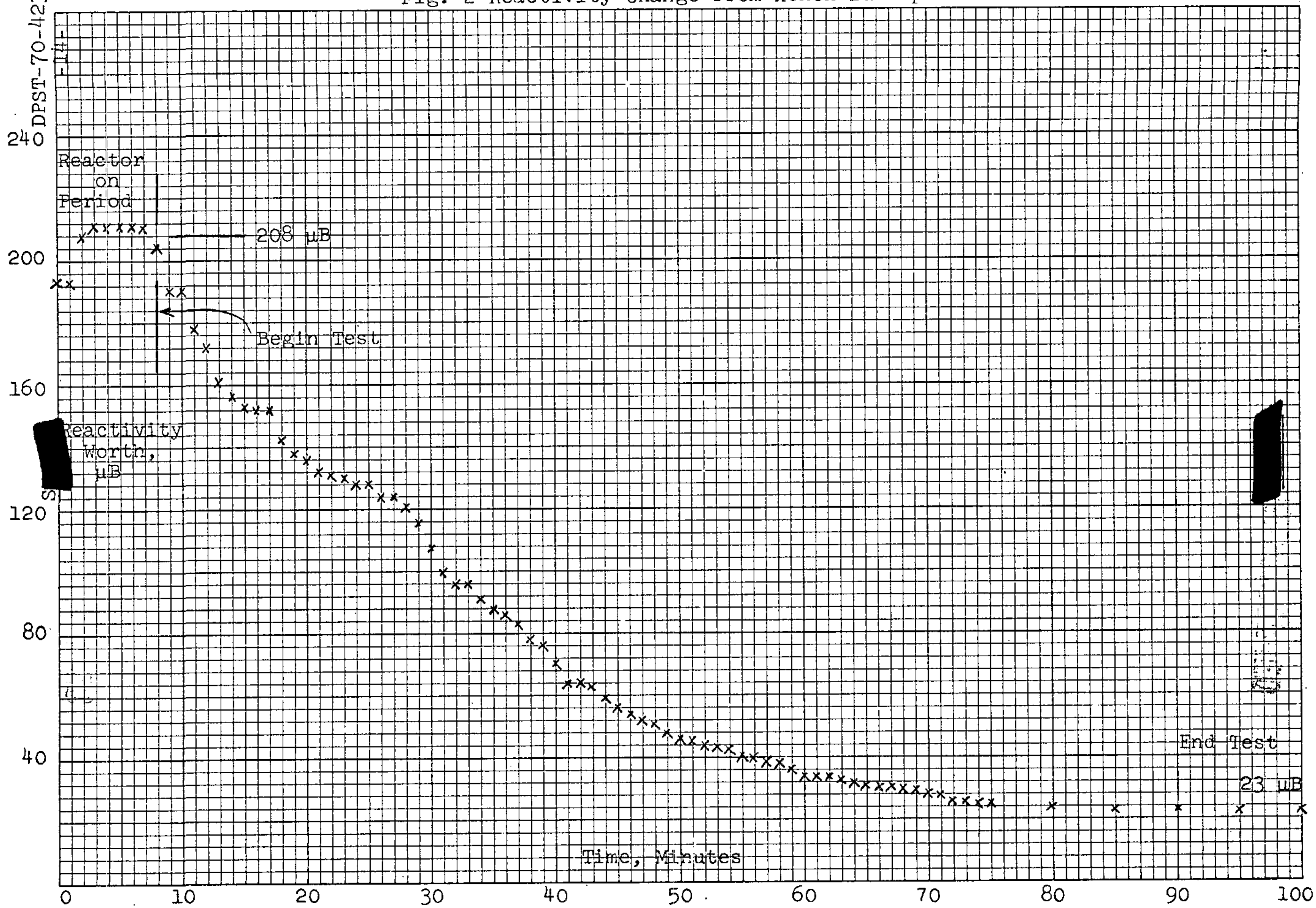

Fig. 3 Calculated Lattice Reactivity vs. Time

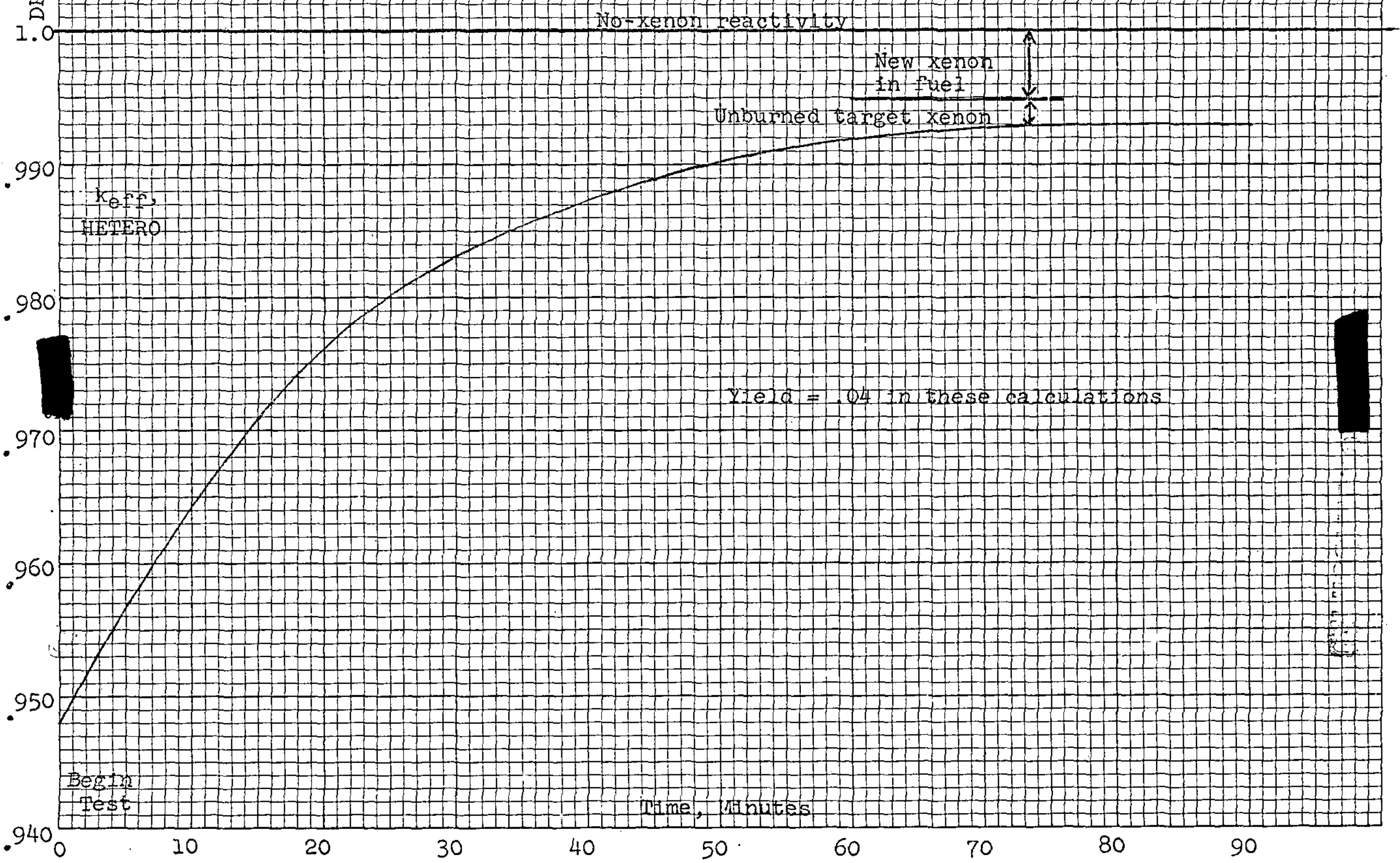

Fig. 4 Change in Xenon Reactivity Worth with Time

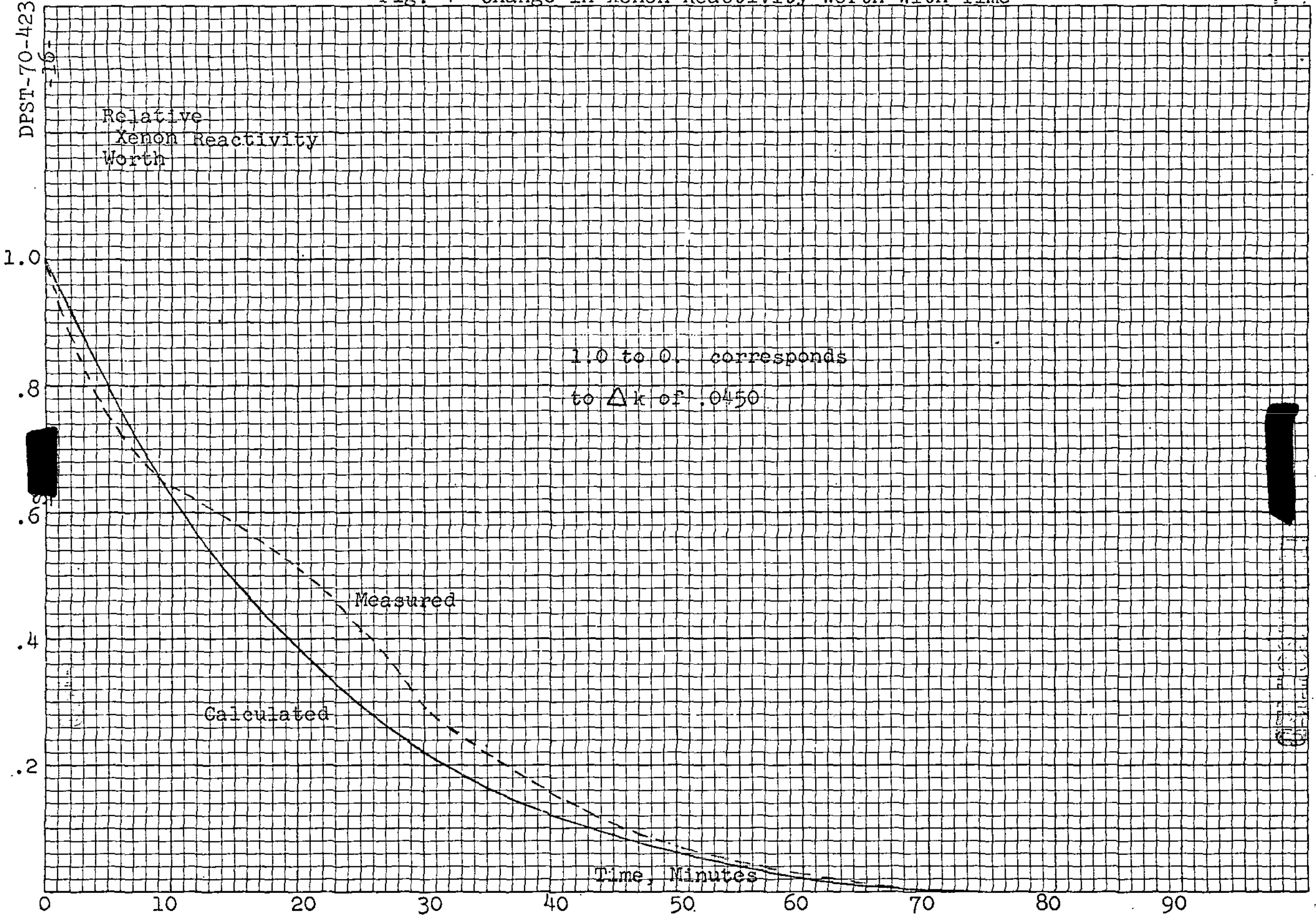

Fig. 5 Ratio of Xenon Worth to Initial Target Xenon Worth vs. Time